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Evaluation of satellite-derived precipitation along the west coast of the United States.

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NAVAL POSTGRADUATE SCHOOL
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EVALUATION OF SATELLITE-DERIVED
PRECIPITATION ALONG THE WEST COAST
OF THE UNITED STATES

by

Michael D. Pind

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Thesis Advisor: C.H. Wash

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Evaluation of Satellite-Derived Precipitation along the West Coast of the United States

by

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ABSTRACT

Four satellite estimation techniques were applied to twelve cases during the winter/spring (1986-87) along the west coast of the United States. These estimates were then compared with observed precipitation patterns from radar and surface observations to evaluate their skill.

Results proved the National Environmental Satellite, Data and Information Service (NESDIS) subjective technique superior. Other methods were IR threshold, color bispectral and the Naval Postgraduate School (NPS) bispectral minicomputer program. All techniques overestimated observed precipitation, but the NESDIS method substantially reduced the amount of over-estimation. All techniques showed excellent alignment and were more successful representing the western edge rather than the eastern edge of precipitation. Only the NESDIS and NPS bispectral approach showed skill in depicting precipitation intensity.

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I. INTRODUCTION

For the past decade, Naval Oceanography was centralized around Fleet Numerical Oceanography Center (FNOC), Monterey, CA. Almost every analysis or forecast product was derived or originated from FNOC. The volume of products became so large that their computer facility had little capacity for future requirements. Thus, the current goal of the Naval Oceanography community has been to diversify computer assets by allowing the oceanography centers to maintain computers capable of modifying FNOC products and/or generating their own regional products. In addition to providing the user with more guidance, it also aids the survivability of the entire oceanography network in case of wartime conditions.

As a result of this general diversification, Naval Oceanography regional processing capabilities will rapidly improve over the next five years. This will be accomplished through the development, procurement and distribution of three major equipment suites to the fleet. They are: the AN/SMQ-11 Satellite Receiver, the Naval Environmental Data Network (NEDN) Oceanographic Data Distribution and Expansion System (NODDES) /

Satellite-Data Processing and Display System (SPADS), and the Tactical Environmental Support System (TESS). All three systems have in common satellite processing and display, which enables the oceanographer on the ship or at the remote station to make evaluations of current weather parameters without the assistance of regional centers (e.g. Guam, Pearl Harbor, Norfolk or Rota) or FNOC. In addition, all three systems are scheduled to arrive in the fleet almost simultaneously.

Although ship, aircraft and weapon system technology has advanced steadily over the past decade, oceanography and meteorology continue to play a primary role in the planning and execution of major operations. Satellite capabilities provide the operational command with a passive (i.e., the ability to maintain communication silence) means of obtaining numerous oceanographic and meteorological parameters (e.g., cloud, temperature, wind, moisture, pressure, sea condition, sea-surface temperature, weather element, etc.). The accuracy and extent of these observations have improved dramatically with better satellites, sensors and applications. Thus, it becomes imperative that the Naval Oceanography community utilizes the latest techniques for application of satellite data.

This thesis is designed primarily to evaluate satellite processing and display capabilities for the detection, identification and classification of precipitation over the west coast of the United States. The accuracy of four satellite precipitation estimation approaches will be evaluated using twelve winter/spring cases. Three methods use the Satellite-Data Processing and Display System (SPADS) software packages while a fourth is primarily subjective. Verification is conducted with the National Meteorological Center's (NMC's) radar summary charts and surface observations.

Chapter II of this thesis reviews the problem of monitoring rainfall including key research involving satellite derived precipitation. Chapter III gives a detailed description of the experimental procedure. Chapter IV includes the four precipitation estimation schemes including the National Environmental Satellite, Data and Information Service (NESDIS) technique for identifying precipitation, SPADS bispectral and thresholding techniques, and the current Naval Postgraduate School (NPS) cloud and precipitation model. Chapter V describes the experimental results using a case demonstrating excellent agreement and a case demonstrating poor agreement. The experimental results

for these two cases are provided in detail. The remaining ten cases, analyzed with the same attention to detail, have been summarized in tables for ease in reading. Conclusions and recommendations for all twelve cases are found in Chapter VI.

II. MONITORING RAINFALL: THE NATURE OF THE PROBLEM

A. RAINFALL MEASUREMENT

Barrett and Martin (1981) describe precipitation as one of the most variable elements in weather. It varies with respect to its frequency, duration, intensity and spatial pattern, not to mention its appearance in both solid and liquid forms. Rainfall organization and distribution, influenced by atmospheric circulation, are greatly enriched by global geography. These factors result in rainfall distribution patterns of great complexity.

Conventional techniques for measuring precipitation include the traditional in situ devices (rainguages) and ground-based remote sensing systems (weather radar), both of which have been used successfully during the past twenty-five years. Although these methods provide reliable rainfall data, it is not surprising that monitoring with the desired detail, timeliness and accuracy is often difficult.

Measurement of rainfall by gauges depends on topography, site, wind and gauge design. In addition, accessibility of locations, availability of personnel to

read the instrument, suitable power supply, security of station, ability to communicate readings quickly and accurately, and lack of observation platforms over the oceans magnify the difficulty of using guages to observe precipitation. It is easy to see why better methods are sought.

In the case of the remote weather radar, problems with resolving the proper relationship of backscattered microwave energy to drop spectrum size, attenuation, absorption, reflection and signal calibration all present difficulties in the measurement of precipitation intensity and amounts. Barrett and Martin (1981) indicate that spatial correlation of rainfall decreases rapidly with increasing distance between points (e.g., rainfall at points separated by distances as small as 50 km is practically unrelated). Further discussions of the capabilties and weaknesses of radar measurement are found in Mason (1971), Battan (1973), and Hudlow et al. (1979). However, Barrett and Martin point out that radar does have an advantage over conventional gauges. It is spatially continuous over its prescribed range, usually 125 miles over flat terrain.

B. NEED OF SATELLITE MONITORING

Precipitation plays an important role in weather, climate, hydrology and oceanography. As a primary part of the hydrological cycle, man depends on it as a natural source of generally pure water for use in agriculture, forestry and commerce, which includes transportation, communications and industry. It also supplies the net of heating from condensation within the atmosphere, which is an important input to any global atmospheric/oceanic model. Thus, the significance of monitoring this weather parameter globally grows as modeling techniques improve.

The Navy's interest in precipitation mirrors many of the reasons mentioned above, but also includes tactical requirements. Unfortunately, conventional methods of collecting rainfall data provide little or no coverage over the oceans. Land coverage, often sparse at best, may disappear during a confrontation, such as the recent Falkland Island conflict where Argentina stopped reporting surface observations for the duration of the conflict with England. Other tactical decisions (i.e., ship movements, amphibious landings, carrier operations, etc.) require current information on cloud cover, precipitation, winds and temperature as well as the ability to make accurate short and long range forecasts.

Therefore, the Navy must strive to upgrade its ability to monitor these parameters, especially over the oceans.

Other reasons for using satellites vice conventional methods include the ability to resolve larger spatial patterns, timeliness of observations and a global data base. With the new Naval Oceanography systems, digital satellite data will soon be available to the remote user. Satellite methods for estimation of precipitation will enhance the final analysis and forecast products for both regional and local sites. This thesis will focus on comparing satellite precipitation schemes which provide reliable analysis of synoptic precipitation patterns.

III. EXPERIMENTAL PROCEDURE

A. EVALUATION PROCEDURE

The central west coast of the United States served as the evaluation region for this investigation. This geographical location was selected for two reasons. First, winter maritime weather systems, only slightly modified by topography, move through this region on a rather routine basis. And second, two National Weather Service (NWS) radar observation stations are located near the center of this area to provide reliable verification of satellite imagery through use of automated radar summary charts.

The satellite methods of mapping precipitation studied were based on visible and infrared imagery. Although passive microwave techniques are being developed, there were no operational microwave data available. Futhermore, the GOES imagery could be collected every 30 minutes which meant images could be selected which closely coincided with Radar Summary Chart times. This would not have been possible with microwave data since they come from a polar orbiting satellite and orbit times vary daily.

GOES visible and infrared imagery was collected on the Global Acquisition and Data Handling System (GADHS) at the Naval Environmental Prediction Research Facility (NEPRF) in Monterey, CA. The data were collected over a five-month period from November 1986 to March 1987. From that data set, twelve cases were selected by the following decision criteria. If automated radar summary charts indicated precipitation within the region under investigation, GOES imagery along with temperature field data from FNOC were collected. If the imagery and field data were collected with no problems, then surface data were ordered for the closest synoptic hour. A satellite analysis of the imagery was completed using four techniques. These techniques are described in the next chapter. Finally, comparisons between results using these techniques and actual radar and surface observations were made and evaluation statistics derived.

B. TYPES OF VERIFICATION

1. Radar Summary Charts

The automated radar summary chart, produced by the National Weather Service, was a major verification tool for this project. Imagery were received to coincide as near as possible with the times on the radar summary chart. The radar information was then transferred

manually from the radar summary chart, on a polar stereographic projection, onto a GADMS mercator background of the eastern north Pacific ocean and the western United States. A viewgraph of the precipitation pattern was taken and compared with satellite estimation techniques.

2. Surface Observations

Surface observations were used to supplement the radar summary charts. Data for the nearest synoptic hour were collected from NPS's archives and FNOC's data bank. NPS archives provided surface charts with excellent coverage over the area of interest. FNOC charts provided sparse data over the area of interest but added ship observations to the immediate west. Together, the two sources provided good coverage of the area of interest and adjacent ocean. For some cases, however, surface observations were given more weight than the radar summary chart since the images and surface observations occurred at the same exact time. In these cases the radar summary chart was valid 30 minutes following the image time.

IV. EXPERIMENTAL TECHNIQUES

A. NESDIS TECHNIQUE FOR SHORT RANGE FORECASTING OF PRECIPITATION

The NESDIS technique, developed by Scofield and Spayd (1984), uses geostationary satellite imagery for estimating precipitation from extratropical cyclones during the winter season. They divide extratropical cyclones into five categories. Each category is defined by distinct cloud pattern evolution and IR enhancements which indicate where the light, moderate and heavy precipitation should occur. From this analysis, short range (1- to 3-hour) forecasts are prepared. These techniques are very subjective and usually overestimate precipitation intensities and amounts, as indicated in Scofield et al. (1982) and Scofield and Spayd (1983).

Scofield and Spayd (1984) schematics of cloud patterns associated with precipitation were developed by examining IR data for various types of winter storms. The schematics are used as aids in analyzing the location and magnitude of continuous or showery precipitation using IR threshold and cloud pattern structure within the winter storm clouds. Images of this technique, produced operationally by the regional National Weather Service

(NWC) forecaster at Redwood City, CA, and sent out over the UNIFAX circuit, will be compared to observed precipitation patterns in the twelve validation cases.

There are five basic types of cloud patterns. They are: comma head category, baroclinic leaf category, subsynoptic-scale wave category, cloud band category, and overruning category. More details on these categories are provided in the case by case analysis. The NESDIS method differs substantially from the objective methods in that it is a product with human input. The comparison of both subjective and objective approaches will assess the role of human decisions in satellite precipitation estimation.

B. SATELLITE DATA PROCESSING AND DISPLAY SYSTEM (SPADS) TECHNIQUES

1. Infrared Thresholding

Infrared thresholding is the original subjective technique (i.e., digital data transformed to shades of gray or colors) used for mapping precipitation. However, due to its inability to easily distinguish between thin and thick cold clouds, Barrett and Martin (1981) conclude that IR thresholding is only effective when working with isolated convective activity. Otherwise the technique consistently overestimates the observed precipitation pattern.

There are numerous image enhancements designed to isolate precipitating clouds. Current objective methods use more sophisticated means of thresholding to distinguish types and intensity of precipitation. Because all of the methods described here use IR data in threshold form, it is presented here as an analysis technique.

A range of IR thresholds are used in identifying a rain/no rain condition. Some models, like the NPS model, use two threshold cutoffs (i.e., 247.5 K and 223 K) for discriminating light and moderate intensities of precipitation. Due to the many accepted standard thresholds, this technique produces an image of a specific range of cloud-top temperatures (i.e., 218 K to 258 K) likely associated with precipitation. The range was selected after reviewing articles by Scofield and Oliver (1977), Negri and Adler (1981), Paul (1983), and Spray (1985) which documented their IR threshold ranges of 193 K to 243 K, 229 K to 260 K, less than 247.5 K to 254 K and less than 246 K to 254 K respectively.

In addition, a range of cloud-top temperatures are recorded for each case study to be presenterd in figure form later in the thesis. The ranges coincide

with active precipitation areas from the radar summary chart and surface observations. Then, these ranges are compiled and presented in graphical format for use in comparing past east coast results with this season's west coast results.

2. NPS Geostationary Satellite Cloud and Precipitation Analysis Model

Wash et el. (1985) describes an automated cloud and precipitation analysis scheme. The precipitation estimation method is a modified version of Liljas's (1982) threshold technique adopted from the results of Muench and Keegan (1979). The precipitation module activates if the cloud-type registers as nimbostratus or cumulonimbus. Intensity depends on infrared and visual values; the colder infrared temperatures and brighter visual albedos produce heavier intensities. As indicated before, the infrared precipitation threshold consists of two values (247.5 K and 223 K), which equate to light and moderate precipitation respectively. The values vary slightly because they are dependent upon observed temperature profiles.

3. Bispectral

Due to time constraints, it may not be possible at sea using a TESS system to execute a complete cloud analysis model. A simpler bispectral approach, using both

visible and infrared data, has been developed for SPADS software. The bispectral technique combines both visible and infrared images and overlays the two images in different colors (e.g., IR-red and VIS-green). Where the images combine to produce different shades of orange and yellow, the technique indicates significant cloud thickness (visual) and cold (high) cloud-tops (infrared), giving a strong probability of precipitation. The closer the shading comes to a pure yellow the greater the thickness and the colder the cloud-top temperature, which would indicate a heavier intensity.

The SPADS high quality color display is an efficient method of showing bispectral satellite data. Barrett and Martin (1981) discuss key precipitation studies using bispectral methods. The most successful application has been by Lovejoy and Austin (1979), where radar data guides the choice of critical thresholds.

V. EXPERIMENTAL RESULTS

The evaluation results are now presented. To illustrate the evaluation procedure, attention is focused on two of the twelve cases, a case with excellent and a case with poor agreement. Results from all twelve cases are then summarized in Tables 1 - 12. Each case looks at all four of the experimental techniques mentioned in the previous chapter and makes a subjective comparison of actual radar and surface observation coverage.

The satellite estimates of precipitation from each of the four techniques is compared to the observed radar data for the central west coast region of the United States. An overlay of the radar coverage is placed over the satellite estimates. Attention is first focused on the area of the satellite estimate that is verified by the radar and surface data. Preferably. satellite estimation techniques should have been compared with digital radar observations to generate objective threat scores (i.e., comparison of two fields or patterns; amount of overlapping area divided by the overall area of both fields to yeid a percentage). However, digital radar

observations could not be obtained to correspond to the image times. Therefore. a subjective threat score is determined by comparing the correct area with the overall analysis and verification areas. Two types of patterns were found in these evaluations. The majority of satellite estimates were larger than the observed radar or surface observation pattern. So the threat score was a percentage of the satellite estimate. In the few cases where the radar and surface observation areas were larger than the satellite estimates, the threat score was the percent of the rain area correctly classified by the satellite method. The percentage is evaluated subjectively with an estimation error of approximately ten percent. Since the percentage of agreement is subjective, four categories are utilized to describe the results. The categories are: Excellent Agreement -greater than 75%, Good Agreement -between 50-75%, Fair Agreement - between 25-50%, and Poor Agreement - less than 25%. Next, each technique is compared with the observed precipitation and classified as either an over- or underestimation. In two cases (i.e., 2 and 11), it overestimates the northern portion of the frontal band while it underestimates the southern tail of the frontal band.

A third evaluation criterion is the alignment of satellite-estimated precipitation compared to that of the observed area. The criterion for deciding alignment involves the orientation of the overall satellite estimates compared with the orientation of the radar and surface observation data. If the alignment axis of the precipitation pattern varied by more than 20 degrees (i.e., north to north-northeast), it was considered incorrect. Otherwise the alignment was considered correct.

Precipitation intensity was also verified by subjectively comparing the satellite estimation with the information provided on the radar summary chart and surface observations. The evaluation was characterized as either an overestimate, underestimate or correct.

A fifth evaluation criteria was the accuracy of the leading edge of precipitation. The leading edge of precipitation, normally the eastern edge, coincided with the onset of precipitation and is a critical forecast variable. The leading edge was considered correct if the satellite estimate and observed data agreed within two degrees of longitude. Otherwise, the technique's leading edge was labelled either substantially east or west of the observed precipitation edge.

Since radar summary charts were initially selected as the most representative method of presenting precipitation patterns for comparison, most of the imagery were taken at 30 minutes after an intermediate synoptic or synoptic hour which was within five minutes of the radar summary chart time. Thus, surface observations, taken approximately ten minutes before the hour, provide only a secondary tool in making these qualitative comparison. However, there are two in which the imagery were taken exactly on the synoptic hour. In these cases more credence is given to the surface observation charts.

A. CASE NUMBER 9 (EXCELLENT AGREEMENT)

The National Meteorological Center's (NMC's) Mean Sea Level (MSL) pressure analysis, for 2300* GMT on 9 February 1987 (not shown), shows a fast moving cold front located along the west coast of the United States. It is approaching a weak wave originating from an upper-level perturbation located over northern California. Weak high pressure dominates the remainder of the western United States. The visible and infrared images, Figs. 1 and 2 respectively, depict the complex cloud structure

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*NMC failed to produce a 2100Z surface analysis.

associated with this situation. The visible image shows a distinct comma cloud with its center located at approximately 49.0° N and 131.5° W. Both visible and infrared images indicate an unusual bulge in the frontal cloudiness over northern California.

The radar summary chart for 2135Z (Fig. 3) shows light to moderate rain and rainshowers occurring from Astoria, OR southward to Los Angeles, CA. The entire area of precipitation is moving northeast at 25 to 30 knots. Rainfall intensities increase over northern California, probably in relation to the weak wave developing in that region. Coastal precipitation observations, depicting rain and rainshowers from Astoria, OR southward to Los Angeles, CA, increase confidence in the area precipitation coverage portrayed by the radar summary chart.

The NESDIS technique, developed by Scofield and Spayd (1984), identifies the frontal zone as a Cloud Band pattern. The IR schematic of the NESDIS Cloud Band Category can be seen in Fig. 4. The weak wave was identified as a Subsynoptic-Scale Wave in an overrunning zone. Its IR schematic can be seen in Fig. 5. The schematics of evolution of cloud patterns associated with moderate to heavy precipitation are used by the NWS

Redwood City forecaster to aid in analyzing the location and magnitude of the continuous or showery precipitation. Scofield and Spayd (1984) describe both categories as follows:

> Cloud Band: Cirrus clouds comprise most of the cloud band. However, those bands which possess low-level tails are active (contain precipitation). In addition, when newer cloud bands develop in the rear portions of the baroclinic zones, the older bands in the front portions of the baroclinic zones often dissipate.

> Subsynoptic-Scale Wave: At times the wave appears to develop in an area of convection along the southern portion of the baroclinic zone and propagates northeastward along the zone.

Comparisons of the operational Redwood City NESDIS product, as seen in Fig. 6, with observed radar and surface observation precipitation patterns indicate estimates that are classified as excellent agreement. By the size and intensity of shower activity, the Subsynoptic-Scale Wave schematic (Fig. 5) using T+4 hours shows the best correlation. The alignment of the precipitation patterns is extremely good, intensities showing light rain and rainshowers are slightly overestimated, and overlapping area coverage as related to threat score is close to 90%. The leading edge of the precipitation pattern is excellent except over a small section of northern California where the technique

underestimates the actual precipitation pattern slightly to the west.

The IR threshold technique observed in Fig. 7 is classified as excellent agreement. Overlapping area coverage is 95%, alignment and leading edge are exact. However, intensities (i.e., colder cloud-top temperatures) are again overestimated along the Oregon coast. IR enhancements indicate that temperatures in the range of 228 K to 243 K best represent the pattern outlined in the radar summary chart for case number 9. As indicated before, results from all cases will be placed in graphical format for comparison with mean thresholds derived from previous studies.

The NPS model results observed in Fig. 8 is classified as excellent agreement (i.e., area coverage is 75%). Again, the technique overestimates the leading edge of precipitation in the mountains northeast of Sacramento but otherwise the rest of the pattern is correct. And as stated above, radar and surface observation coverage in this region is suspect. The model indicates areas where more intense precipitation is likely, and like the NESDIS technique, it indicates rainshowers occurring throughout the precipitation band. The alignment is correct.

The bispectral image observed in Fig.9 is classified as excellent agreement. Area coverage is 90%. Bright yellows highlight all areas of precipitation. However, the area of bright yellows actually exceeds the area of precipitation over the mountains northeast of Sacramento, California. Since the radar cannot see over the mountains and surface reports are extremely sparse in this region, it remains inconclusive whether the bispectral representation is overestimating the actual precipitation at all. Otherwise the leading edge is correct. The alignment of the area is exact. Precipitation intensity is difficult to estimate using the bispectral method because it is hard to determine when the shade of yellow is getting brighter. But it appears that the brightest yellows are again north of the weak wave.

Table 9 contains a summary of all the information above. All methods received an excellent score, but the NESDIS and bispectral techniques scored slightly higher. The NESDIS and IR techniques underestimated the area coverage while the other two methods overestimated it. All techniques overestimated the intensity of precipitation, showed correct alignment and properly defined the leading edge of precipitation.

B. CASE NUMBER 1 (POOR AGREEMENT)

The NMC MSL pressure analysis for 1800 GMT on 4 December 1986 (not shown) displays a weak cold front approaching the west coast of the United States. The visible and infrared imagery, Figs. 10 and 11, show a comma shaped cloud with its center located at 40.5° N and 130.1° W. A massive cirrus shield overshoots the active frontal zone by nearly 700 nautical miles. A weak stationary front still lingers along the border of Washington and Oregon, further enhancing the prefrontal cloudiness.

The NMC radar summary chart, seen in Fig. 12, shows broken areas of precipitation from northern Washington southward to central California. The areas of precipitation are moving eastward at 15 to 20 knots. The surface analysis for 1800 GMT only indicates rainfall occurring at one coastal station in Oregon. Thus, it does not add much confidence to the radar depiction. However, the radar summary chart time, 2135 GMT, is closer to the image time than the surface observation chart. So it is used as the primary verification tool in this case.

The NESDIS technique classifies the synoptic situation above as a Cloud Band category. Discussed in case number 9 and illustrated in Fig. 4, this case

emphasizes the importance of cloud structure, especially as it relates to those bands with low level tails. The NESDIS analysis technique, shown in Fig. 13, severely underestimates the amount of precipitation actually occurring along the west coast and therefore exhibits poor agreement with the radar summary chart. However, it does capture the second system off shore. The NESDIS approach in a cloud band case focuses attention at the immediate cloud bands (using the cloud tails as a guide). The large mid and high cloud shield ahead of the bands is correctly classified as no precipitation. The error in this case is to underestimate precipitation in the first band. Fig. 13 is a working copy of the NESDIS technique supplied by the NWS, Redwood City, CA forecasting center. The red markings on the picture should be ignored since they represent a short range forecast and are not related to this study. Area coverage or threat score in the region of interest is approximately 15% which classifies the estimation technique as poor agreement. The alignment of the precipitation pattern is also poor. However, the misalignment, in part, is probably due to the initial analysis. Although the first baroclinic zone is severely underestimated, there is enough depicted to clearly identify the leading edge of precipitation. Since a

stronger baroclinic zone is developing to the rear of the first zone, intensities are correctly depicted by showing light precipitation occurring along the eastern baroclinic zone.

In Fig. 14, the IR threshold technique is classified as poor agreement. Overlapping area coverage is 20%. The large cirrus canopy in advance of the frontal band creates a significant overestimation of the precipitation pattern, projecting the leading edge of precipiation substantially to the east. Orientation is also distorted since the IR enhancement slants northwest to southeast while the radar depiction slants north to south. Cloud-top temperatures, ranging from 218 K to 243 K, imply changes in precipitation intensity throughout the region, however, all reported intensities are steady and light.

As seen in Fig. 15, the NPS technique is classified as fair agreement. The enhancement curves used in the model do not completely differentiate between the cirrus shield and the frontal band which causes the same over-estimation, but not as gross as stated in the IR technique. Area coverage is 25%. Orientation of the area, unlike the previous technique, is more north to south like the radar summary chart. Intensity over the observed area remains nearly constant which is consistent with the

steady light precipitation pattern depicted on the radar summary chart and, therefore, is classified as correct. Yet the leading edge of the precipitation appears substantially to the east of the observed edge.

The bispectral technique observed in Fig. 16 shows the same problems indicated in the IR threshold technique. Again, area coverage is 20%, which classifies the technique as having poor agreement. The cirrus shield causes the same overestimation. Orientation of the bispectral precipitation pattern axis remains northwest to southeast which differs from the observed pattern. Intensity is not distinguishable since there is little or no shading differences in the frontal zone or cirrus shield. The leading edge of the precipitation is again substantially east of the observed edge.

Table 1 contains a summary of case number 1. All methods are marginally poor cases. The NPS technique seems to do slightly better than the other three satellite estimates. Where all of the other methods overestimate the amount of precipitation occurring, the NESDIS model severely underestimates it. Alignment is incorrect in all techniques except the NPS. Both the NESDIS and NPS methods show correct precipitation intensities while the IR technique overestimate its and

the bispectral underestimates it. Fig. 13 indicates that the NESDIS technique correctly identifies the leading edge of precipitation while all of the other satellite estimates show the leading edge substantially to the east.

C. SUMMARY OF ALL CASES

Table 13 summarizes the evaluations of all twelve cases (Tables 1-12) and provides an overall comparison of the techniques using the calculations derived from all of the cases. Although the percentages do not show many dramatic differences between the techniques, the NESDIS technique is shown to be superior in almost every category. The most likely explanation for this improved capability is the human input in the analysis stategy.

In percentage of area coverage, the IR threshold technique is the least effective (37%). But the other three techniques only show modest to good skill and have scores within ten percentile points of each other (i.e., 52% to 61%). Table 13 shows that all three SPADS techniques consistently overforecast the amount of precipitation, some more than others. But the NESDIS technique, as seen in Table 13, over- and underestimates precipitation equally. Again, inserting human judgement into the analysis strategy seems to improve the overall

area estimation. Another explanation for the low scores seen in all of the techniques is that they may be artifically lower than normal because the selected area of interest did not include the western edge of precipitation. And it was over water, along the western edge of the precipitation, where the technique seems to make its best analysis. Thus, given the area coverage scores alone, one would incorrectly conclude that none of the techniques provide better than good representation of the observed precipitation patterns.

In addition, Table 13 shows that all techniques do an excellent job in getting the correct alignment, but only the NESDIS and NPS methods show adequate skill in predicting intensities of precipitation. The results of the NPS model are extremely promising since there is no man involved in the analysis strategy. The IR technique normally overestimates while the bispectral often underestimates the intensities. Intensities were extremely difficult to evaluate for the bispectral technique. The shades of yellow and orange proved much more difficult to discern than shades of gray. Another factor was the quality of hardware. Poor resolution on the CRT or hardcopy print device caused further hardships in estimating precipitation intensity.

Finally, Table 13 indicates that the NESDIS technique shows excellent skill in depicting the leading edge of the observed precipitation. The SPADS satellite estimation techniques seem to consistently place the leading edge substantially to the east.

Fig. 17 looks at the area coverage percentage scores for all techniques and cases over the winter season from Dec 1986 - Mar 1987. Although no specific pattern is found with this graph, it is easy to pick out the cases (e.g., 2, 4 and 5) where one particular technique did significantly better than the others. It also highlights a gradual improvement of the SPADS techniques as the winter season progressed which is probably attributable to a strengthening of winter storms. Therefore the stronger storms were faster moving and more sharply defined than the earlier slow moving systems.

Table 14 shows the NESDIS category used in each case. Notice that only two (i.e., Cloud Band and Subsynoptic-Scale Wave) of the five basic NESDIS categories mentioned in Chapter IV were used in all twelve cases. This probably stemmed from the initial criteria for selecting cases which required precipitation on the radar summary chart somewhere within the radar umbrella of either

Sacramento, CA or Medford, OR. To accomodate this requirement, several of the other categories, which occur farther to the north, were excluded.

Fig. 18 takes all the cloud-top temperature data collected from all twelve cases and plots it out in a graphical format. As observed in the figure, the top of the mean cloud-top temperature range is approximately 241 K which is close, although somewhat colder, to the threshold range (i.e., 246 K to 253 K) used in models, sighted by Paul (1983). The explanation for this difference is not obvious, but may be explained by the winter season and higher latitude where the cases were selected.

VI. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are derived from results described in Chapter V: 1) the manual (man intensive) NESDIS technique proved superior to the objective SPADS techniques, 2) all techniques overestimated observed precipitation, but the NESDIS method reduced the amount of overestimation and even underestimated by approximately the same amount, 3) all techniques did a better job representing the western edge rather than eastern edge of precipitation, 4) all techniques show excellent alignment, 5) only the NESDIS and NPS methods show skill in predicting precipitation intensity, 6) the NESDIS technique shows excellent skill in depicting the leading edge of precipitaion, 7) the average range of cloud-top temperatures which match radar summary chart patterns is approximately 5° C colder than previous studies indicated.

Precipitation remains one of the most difficult weather parameters to monitor. Current conventional methods (surface and radar observations) of reporting precipitation provide excellent coverage over most of the United States. They provide a timely product which

is used daily in business, transportation and recreation. However, the coverage ends approximately 50 nautical miles offshore and do not aid the Navy's needs to monitor precipitation events across the world's oceans. This thesis illustrates that using digital data from geostationary satellites, combined with proven algorithms and man/machine techniques, provides a reliable product which can be used in the fleet.

The NESDIS technique has been used operationally at several locations across the United States. Its performance is proven and regarded as a technique worthy of transmission over the UNIFAX circuit. Therefore, it is recommended that a thorough study be made of this technique, evaluating all five categories. The evaluation should be made over the open ocean in addition to an overland controlled region. If the evaluation proves that the technique provides excellent correlation with observed precipitation patterns, it is further recommended that a technical manual be developed for use by the Naval Oceanography community. The manual would be available to assist Oceanography centers in producing a precipitation analysis for transmission over the fleet broadcast.

TABLE 1
Comparison of Techniques for Case Number 1
at 1830Z on 4 December 1987

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT cor/incor	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	15	UNDER	INCORRECT	CORRECT	CORRECT
IR	20	OVER	INCORRECT	OVER	SUB. EAST
NPS	25	OVER	CORRECT	CORRECT	SUB. EAST
BI-SPECTRAL	20	OVER	INCORRECT	UNDER	SUB. EAST

TABLE 2
Comparison of Techniques for Case Number 2
at 1830Z on 22 December 1987

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT cor/incor	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	85	OVER	CORRECT	CORRECT	CORRECT
IR	20	OVER/UNDER	CORRECT	UNDER	SUB. EAST
NPS	55	OVER	CORRECT	CORRECT	SUB. EAST
BI-SPECTRAL	65	OVER	CORRECT	UNDER	SUB. EAST

TABLE 3
Comparison of Techniques for Case Number 3
at 1830Z on 28 December 1987

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT cor/incor	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	40	UNDER	CORRECT	CORRECT	SUB. WEST
IR	45	OVER	INCORRECT	OVER	SUB. EAST
NPS	70	OVER	CORRECT	CORRECT	CORRECT
BI-SPECTRAL	40	UNDER	CORRECT	UNDER	SUB. EAST

TABLE 4

Comparison of Techniques for Case Number 4 at 1830Z on 1 January 1987

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT cor/incor	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	90	OVER	CORRECT	CORRECT	CORRECT
IR	40	OVER	CORRECT	OVER	SUB. EAST
NPS	45	OVER	CORRECT	UNDER	SUB. EAST
BI-SPECTRAL	35	OVER	CORRECT	UNDER	SUB. EAST

TABLE 5
Comparison of Techniques for Case Number 5
at 1830Z on 2 January 1987

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT cor/incor	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	75	UNDER	INCORRECT	CORRECT	CORRECT
IR	15	OVER	CORRECT	OVER	SUB. EAST
NPS	45	OVER	CORRECT	CORRECT	SUB. EAST
BI-SPECTRAL	10	OVER	CORRECT	UNDER	SUB. EAST

TABLE 6
Comparison of Techniques for Case Number 6
at 1830Z on 3 January 1987

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT cor/incor	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	55	OVER	CORRECT	CORRECT	CORRECT
IR	20	OVER	CORRECT	CORRECT	SUB. EAST
NPS	40	OVER	CORRECT	CORRECT	SUB. EAST
BI-SPECTRAL	60	OVER	CORRECT	UNDER	CORRECT

TABLE 7
Comparison of Techniques for Case Number 7
at 1830Z on 22 January 1987

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT cor/incor	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	40	UNDER	CORRECT	CORRECT	CORRECT
IR	20	OVER	CORRECT	CORRECT	SUB. EAST
NPS	50	OVER	CORRECT	CORRECT	SUB. EAST
BI-SPECTRAL	60	OVER	CORRECT	CORRECT	CORRECT

TABLE 8

Comparison of Techniques for Case Number 8 at 1830Z on 2 February 1987

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT cor/incor	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	65	OVER	CORRECT	OVER	CORRECT
IR	35	OVER	INCORRECT	CORRECT	CORRECT
NPS	20	OVER	INCORRECT	OVER	SUB. EAST
BI-SPECTRAL	20	OVER	INCORRECT	CORRECT	CORRECT

TABLE 9
Comparison of Techniques for Case Number 9
at 2130Z on 9 February 1987

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT cor/incor	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	90	UNDER	CORRECT	OVER	CORRECT
IR	85	UNDER	CORRECT	OVER	CORRECT
NPS	75	OVER	CORRECT	OVER	CORRECT
BI-SPECTRAL	90	OVER	CORRECT	UNDER	CORRECT

TABLE 10
Comparison of Techniques for Case Number 10
at 2130Z on 12 February 1987

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT cor/incor	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	45	UNDER	CORRECT	OVER	SUB. WEST
IR	65	OVER	CORRECT	UNDER	CORRECT
NPS	80	OVER	CORRECT	CORRECT	CORRECT
BI-SPECTRAL	70	OVER	CORRECT	UNDER	CORRECT

TABLE 11
Comparison of Techniques for Case Number 11
at 1830Z on 13 February 1987

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT cor/incor	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	75	UNDER	CORRECT	CORRECT	CORRECT
IR	40	OVER/UNDER	CORRECT	CORRECT	CORRECT
NPS	45	OVER/UNDER	CORRECT	CORRECT	CORRECT
BI-SPECTRAL	75	OVER	CORRECT	UNDER	CORRECT

TABLE 12

Comparison of Techniques for Case Number 12
at 0030Z on 13 March 1987

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT cor/incor	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	55	OVER	CORRECT	OVER	CORRECT
IR	35	OVER	CORRECT	OVER	SUB. EAST
NPS	85	OVER	CORRECT	CORRECT	CORRECT
BI-SPECTRAL	80	OVER	CORRECT	UNDER	CORRECT

TABLE 13
Summary of Tables 1-12

TECHNIQUE	AREA COVERAGE (%)	AREA COVERAGE ESTIMATE over/under	ALIGNMENT correct (%)	INTENSITY over/cor/under	ACCURACY OF LEADING EDGE OF PRECIP SW/cor/SE
NESDIS	61	42% OVER 58% UNDER	83	25% OVER 75% COR 0% UNDER	17% SW 83% COR
IR	37	79% OVER 21% UNDER	75	50% OVER 33% COR 17% UNDER	33% COR 67% SE
NPS	53	93% OVERR 7% UNDER	92	17% OVER 75% COR 8% UNDER	42% COR 58% SE
BI-SPECTRAL	52	100% OVER 0% UNDER	75	8% OVER 17% COR 75% UNDER	58% COR 42% SE

TABLE 14
NESDIS Catergory and Subjective Skill Compared with Radar and Surface Observations

CASE NUMBER	IMAGE TIME	IMAGE DATE	NESDIS CATEGORY
1	1830Z	4 DEC 86	CLOUD BAND
2	1830Z	22 DEC 86	CLOUD BAND
3	1830Z	28 DEC 86	CLOUD BAND
4	1830Z	1 JAN 87	SUBSYNOPTIC-SCALE WAVE & CLOUD BAND
5	1830Z	2 JAN 87	CLOUD BAND
6	1830Z	3 JAN 87	CLOUD BAND
7	1800Z	22 JAN 87	CLOUD BAND
8	1830Z	2 FEB 87	SUBSYNOPTIC-SCALE WAVE & CLOUD BAND
9	2130Z	9 FEB 87	CLOUD BAND
10	2130Z	12 FEB 87	CLOUD BAND
11	1830Z	13 FEB 87	CLOUD BAND
12	0030Z	13 MAR 87	CLOUD BAND

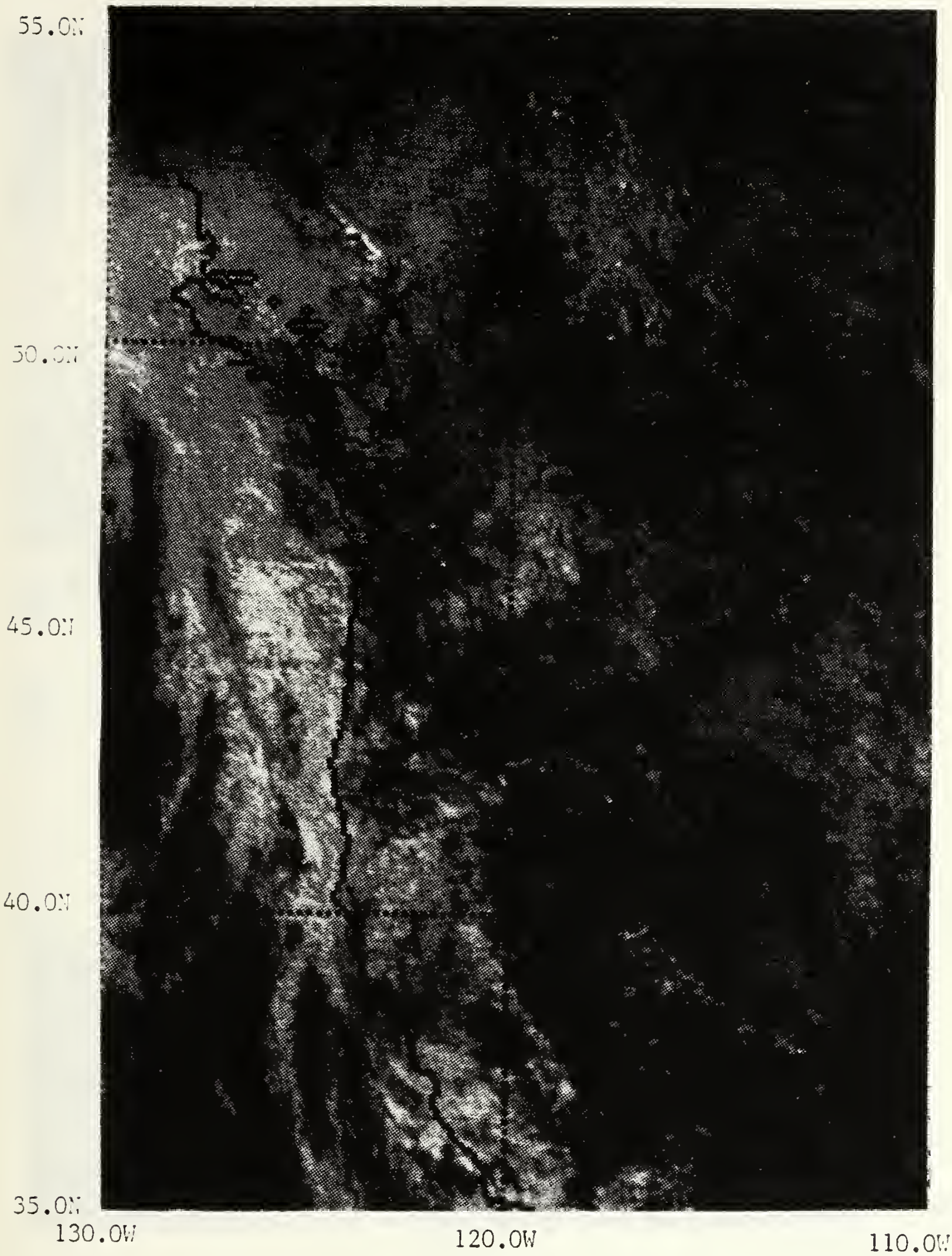

Figure 1. GOES Visible Mercator Image for
2130Z on 9 February 1987

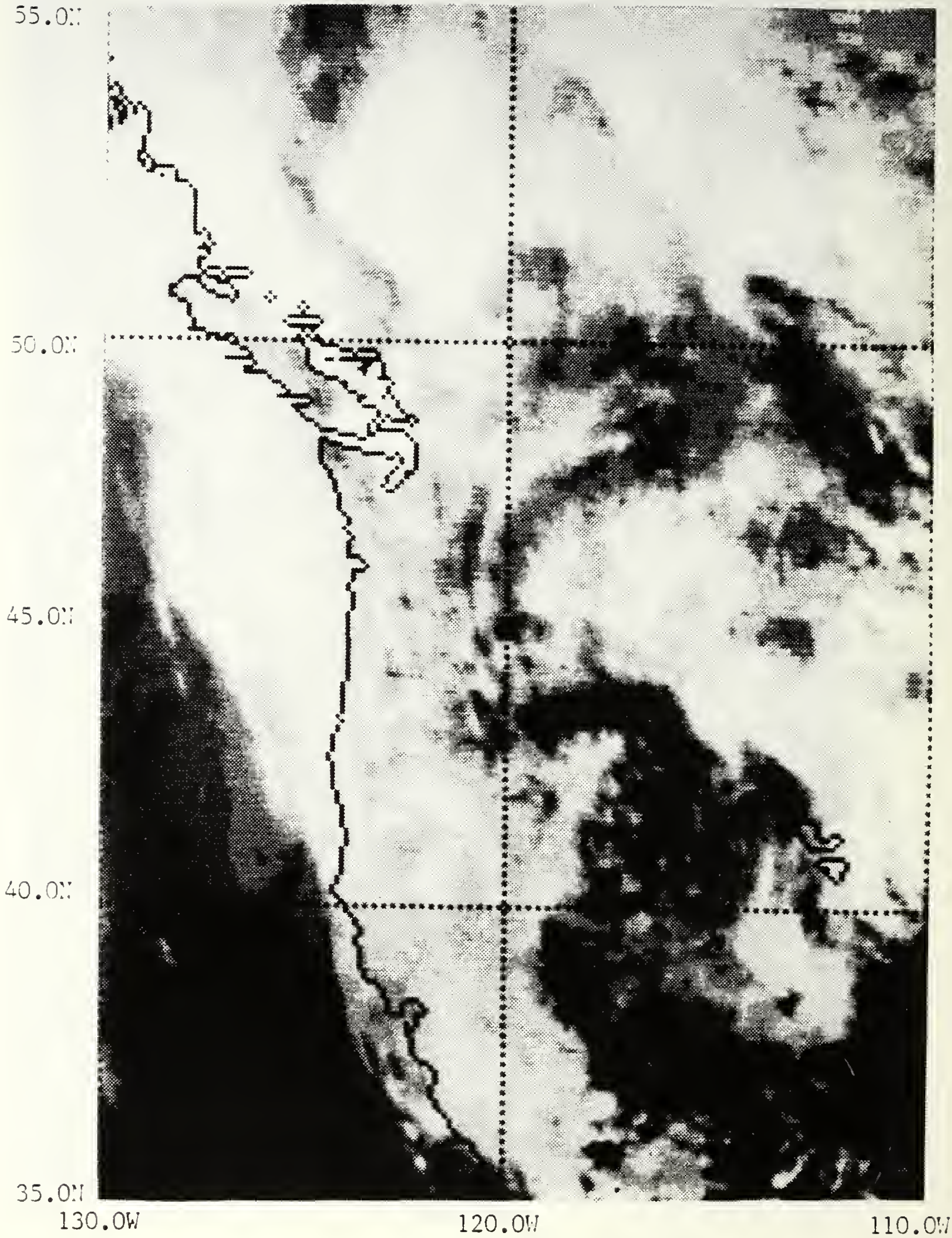

Figure 2. GOES Infrared Mercator Image for
2130Z on 9 February 1987

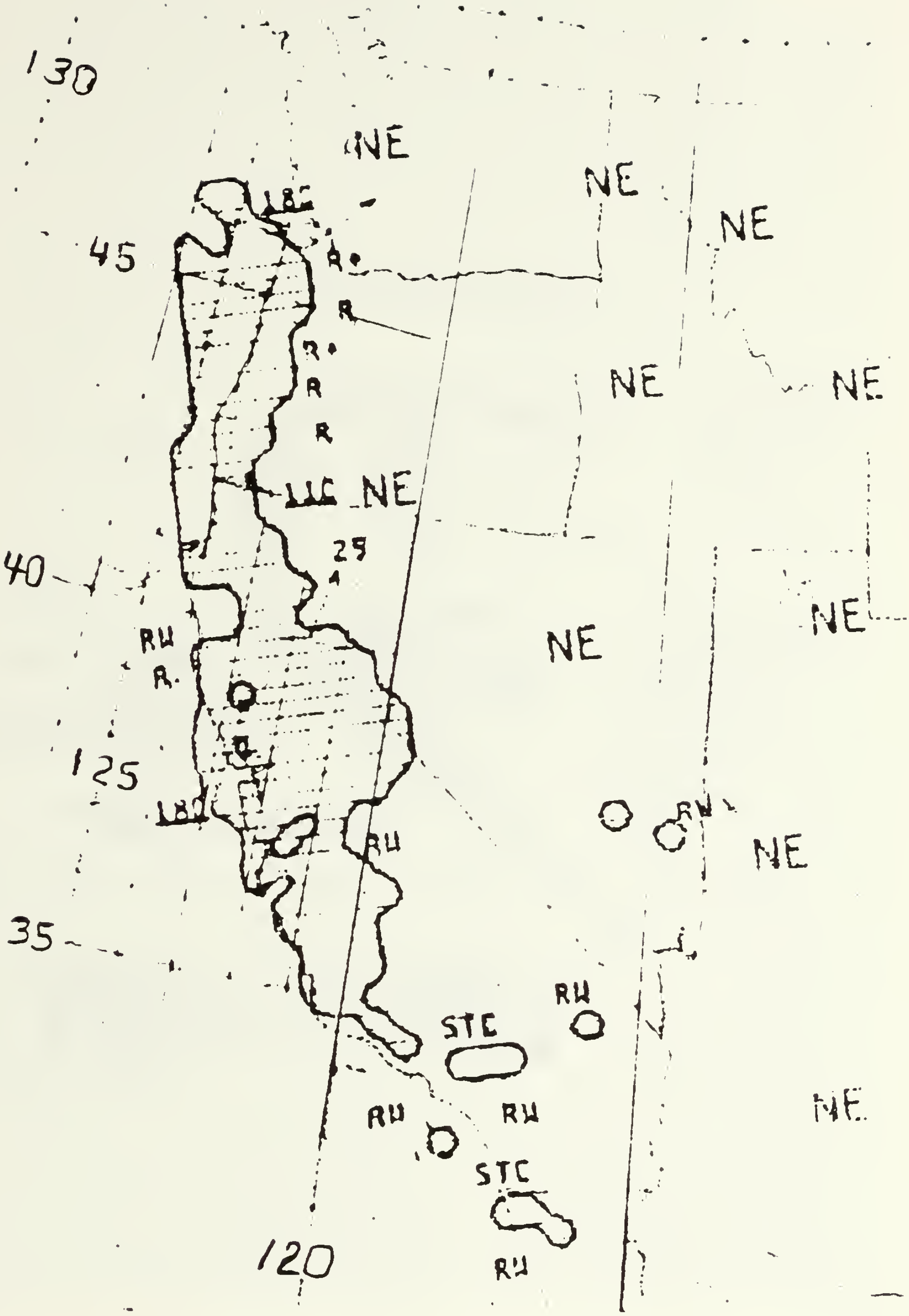

Figure 3. NMC Radar Summary Chart for 2135Z on 9 February 1987

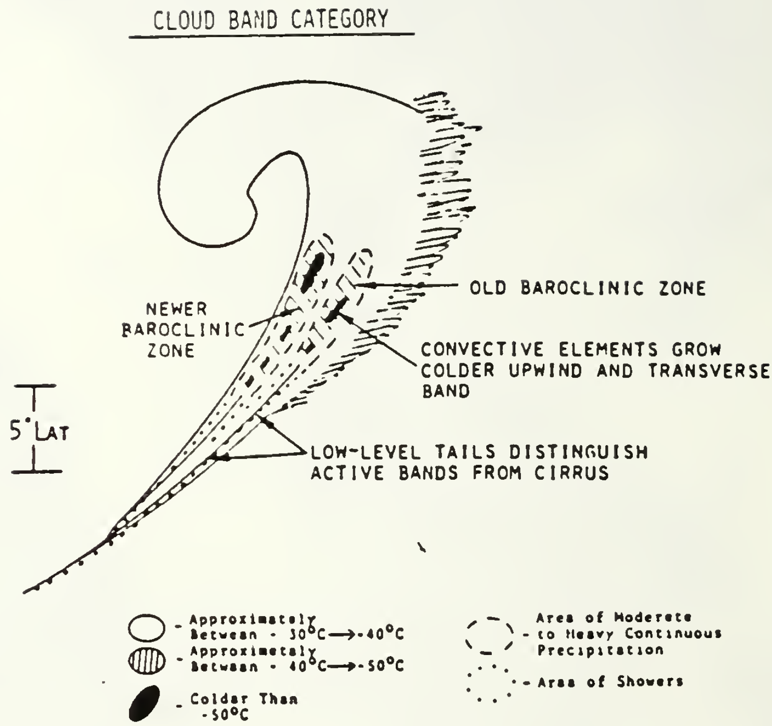

Figure 4. Infrared Schematic of the NESDIS Cloud Band Category from Scofield and Spayd (1984)

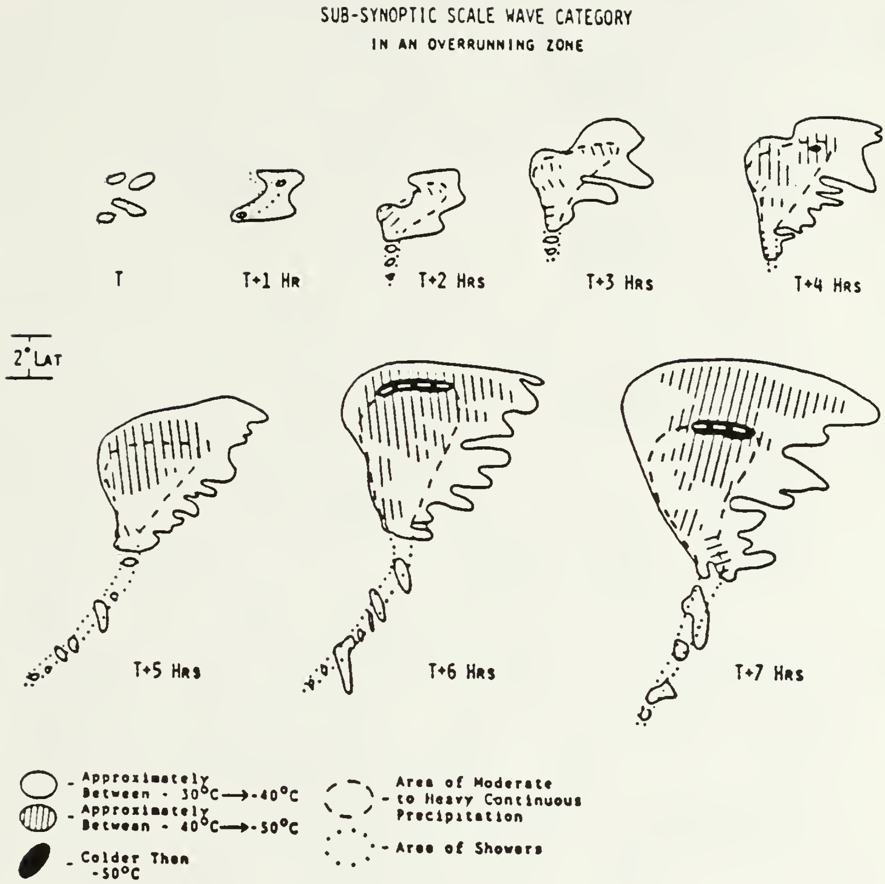

Figure 5. Infrared Schematic of NESDIS Subsynoptic-Scale Wave Category in Overrunning Zone from Scofield and Spayd (1984)

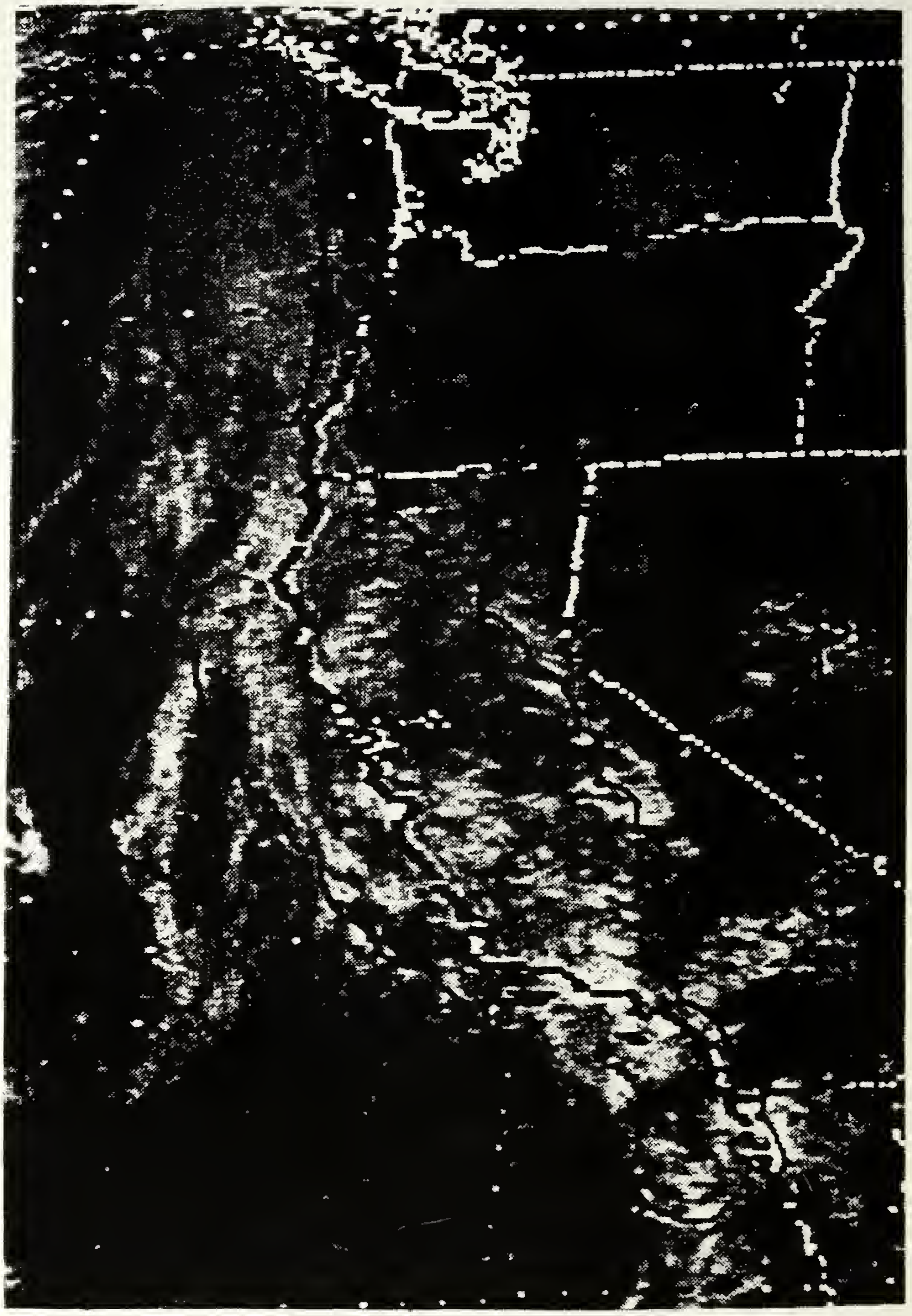

Figure 6. NESDIS Technique overlayed on High Resolution GOES-6 Visible Image for 2100Z on 9 February 1987

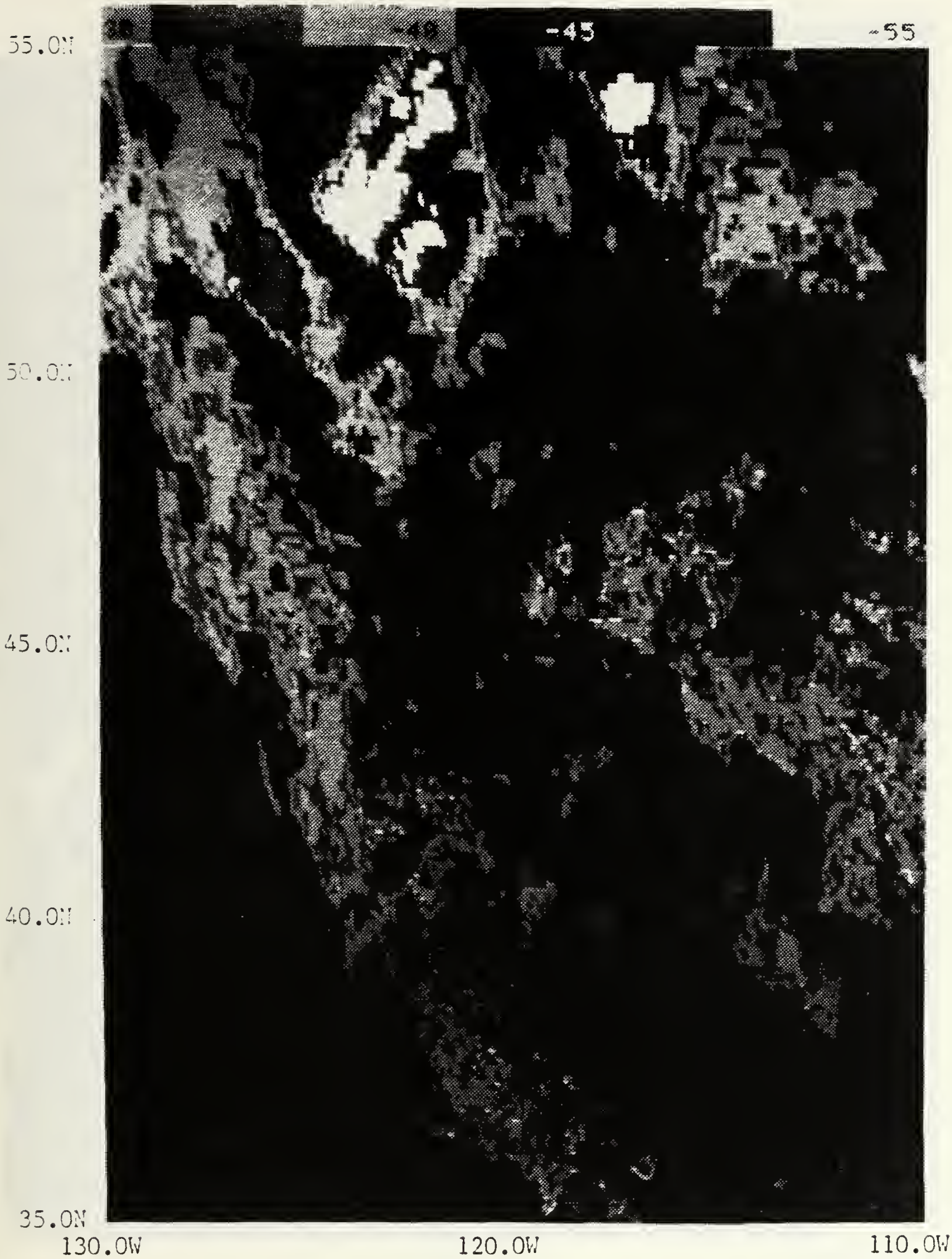

Figure 7. Infrared Technique (-25° C to -55° C)
Image for 2130Z on 9 February 1987

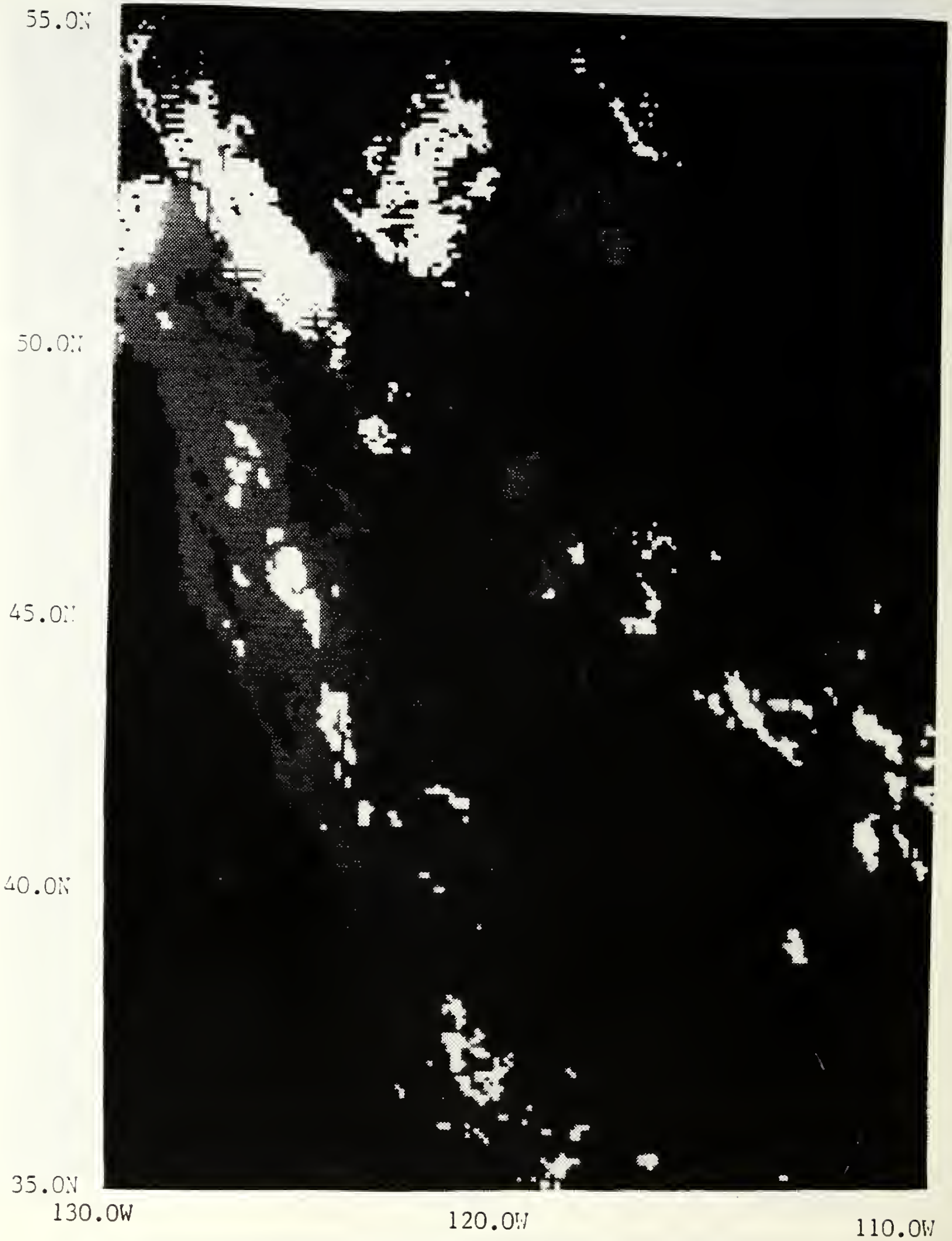

Figure 8. NPS Model Results for 2130Z
on 9 February 1987

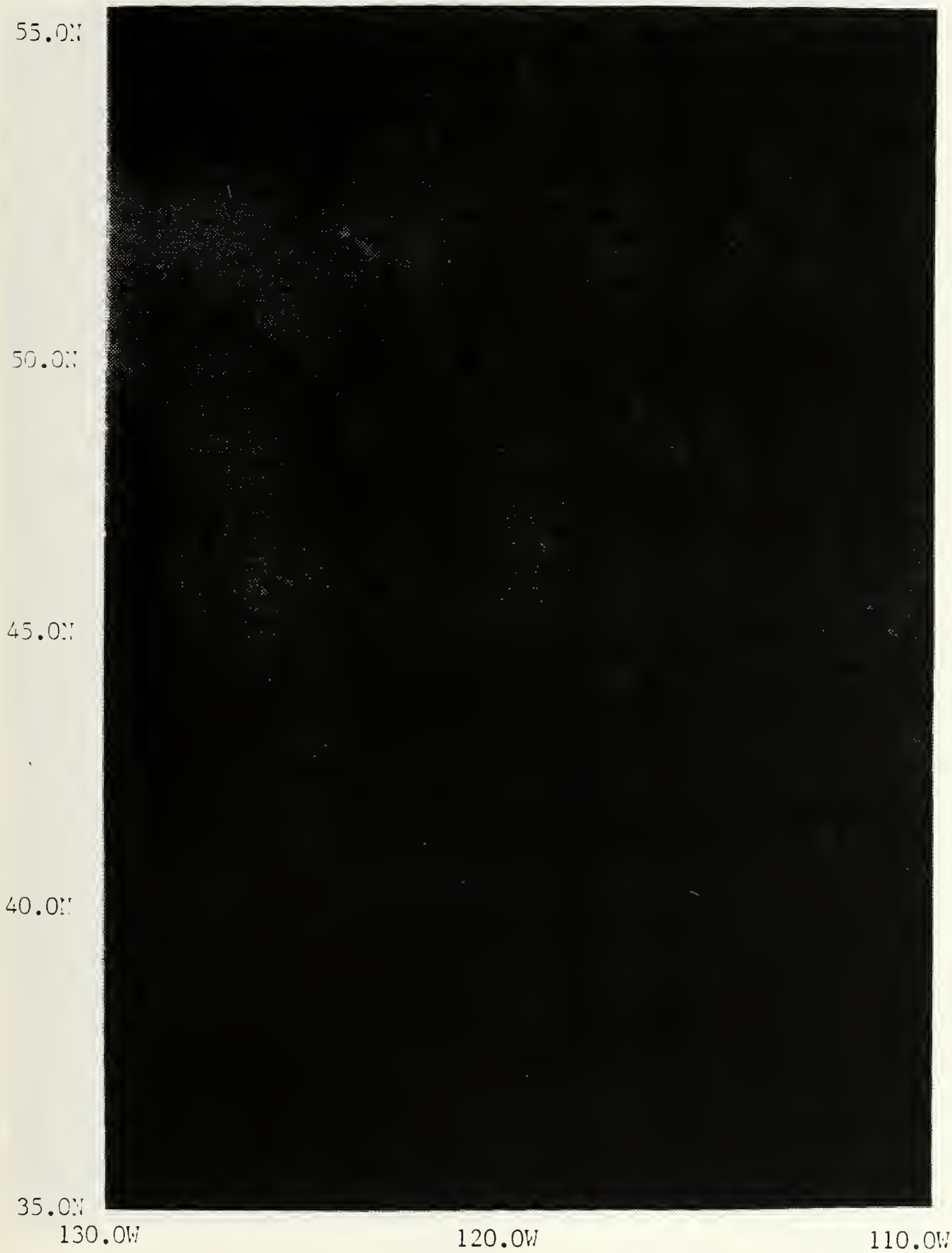

Figure 9. Bispectral Image for 2130Z
on 9 February 1987

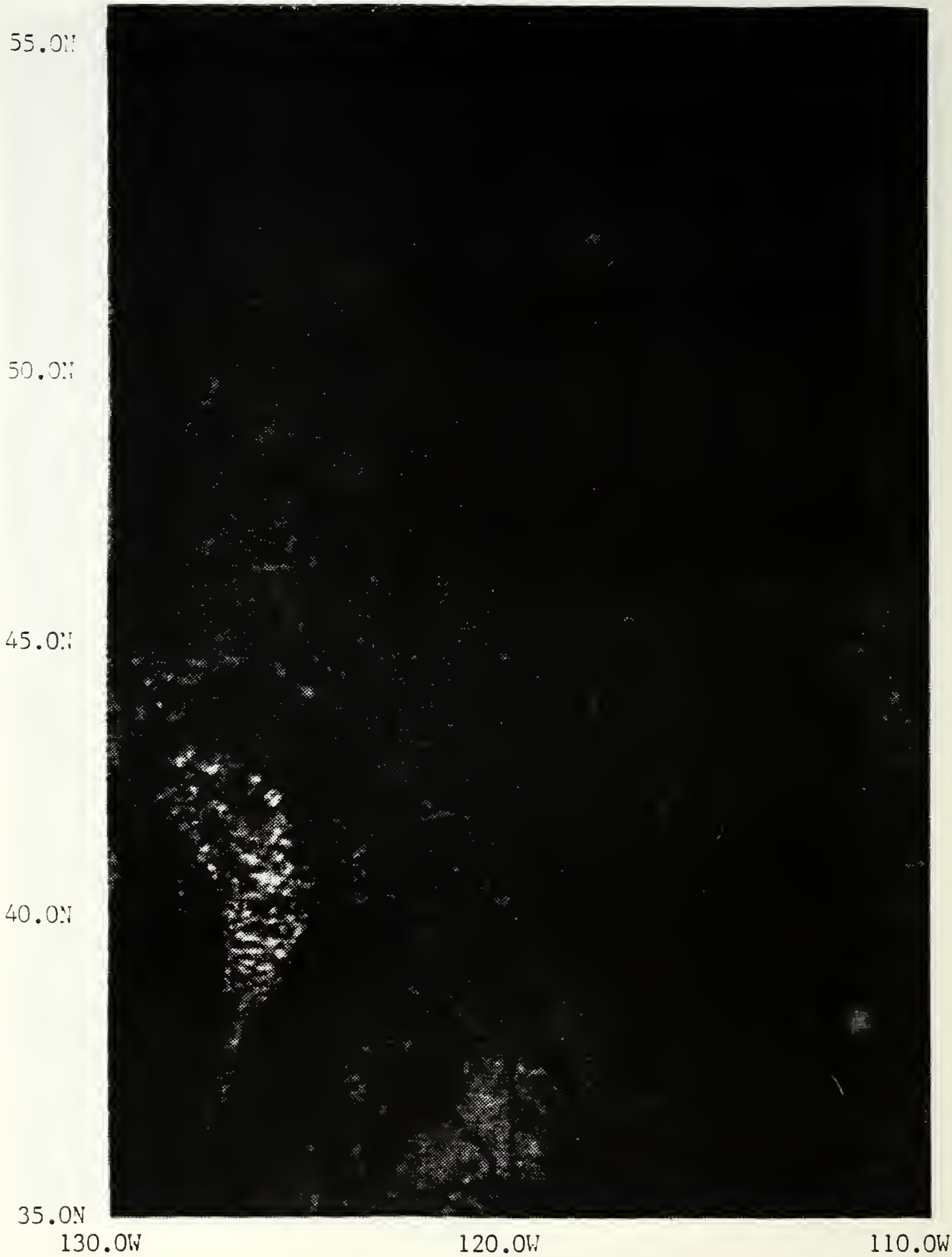

Figure 10. GOES Visible Mercator Image for 1830Z on 4 December 1986

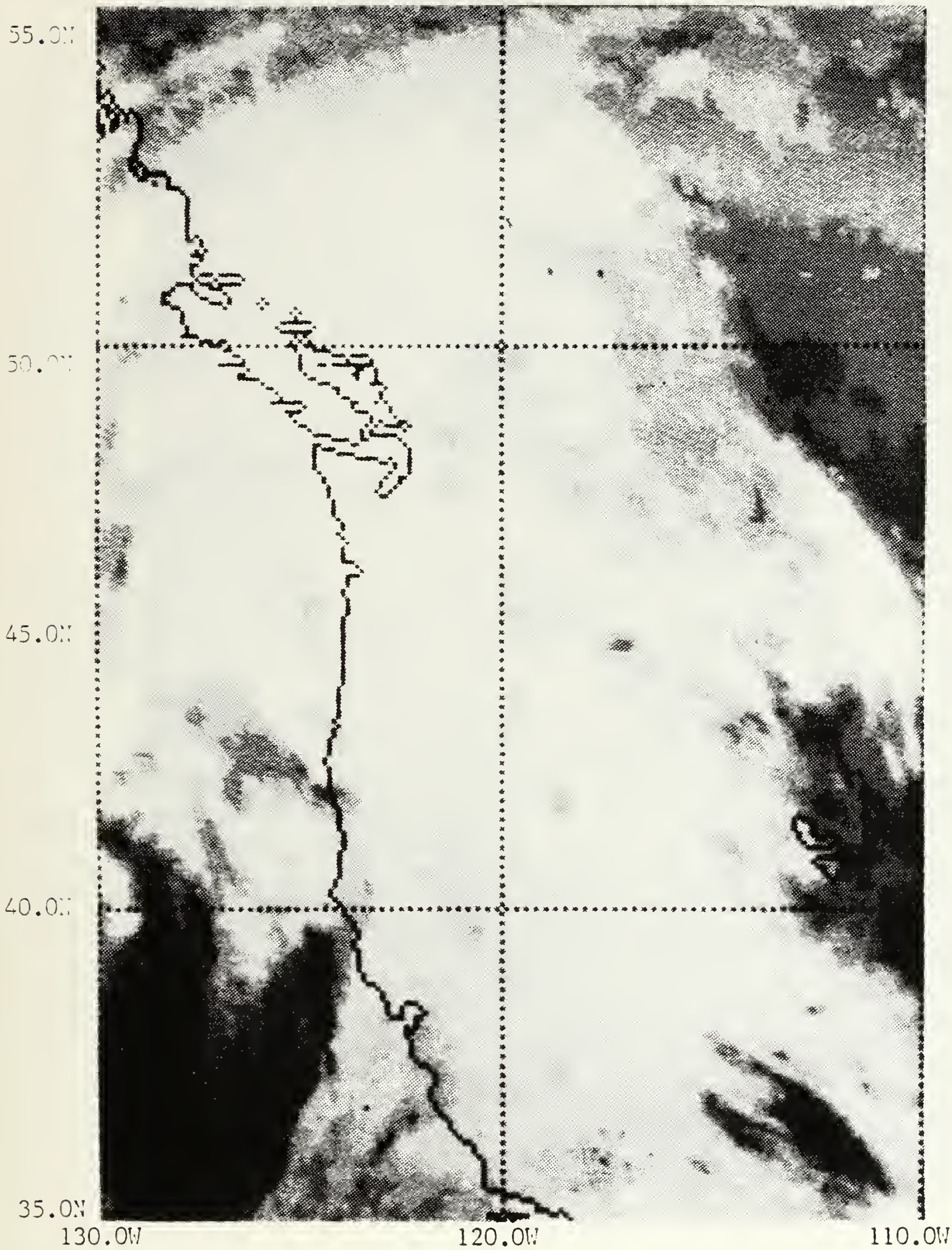

Figure 11. GOES Infrared Mercator Image for 1830Z on 4 December 1986

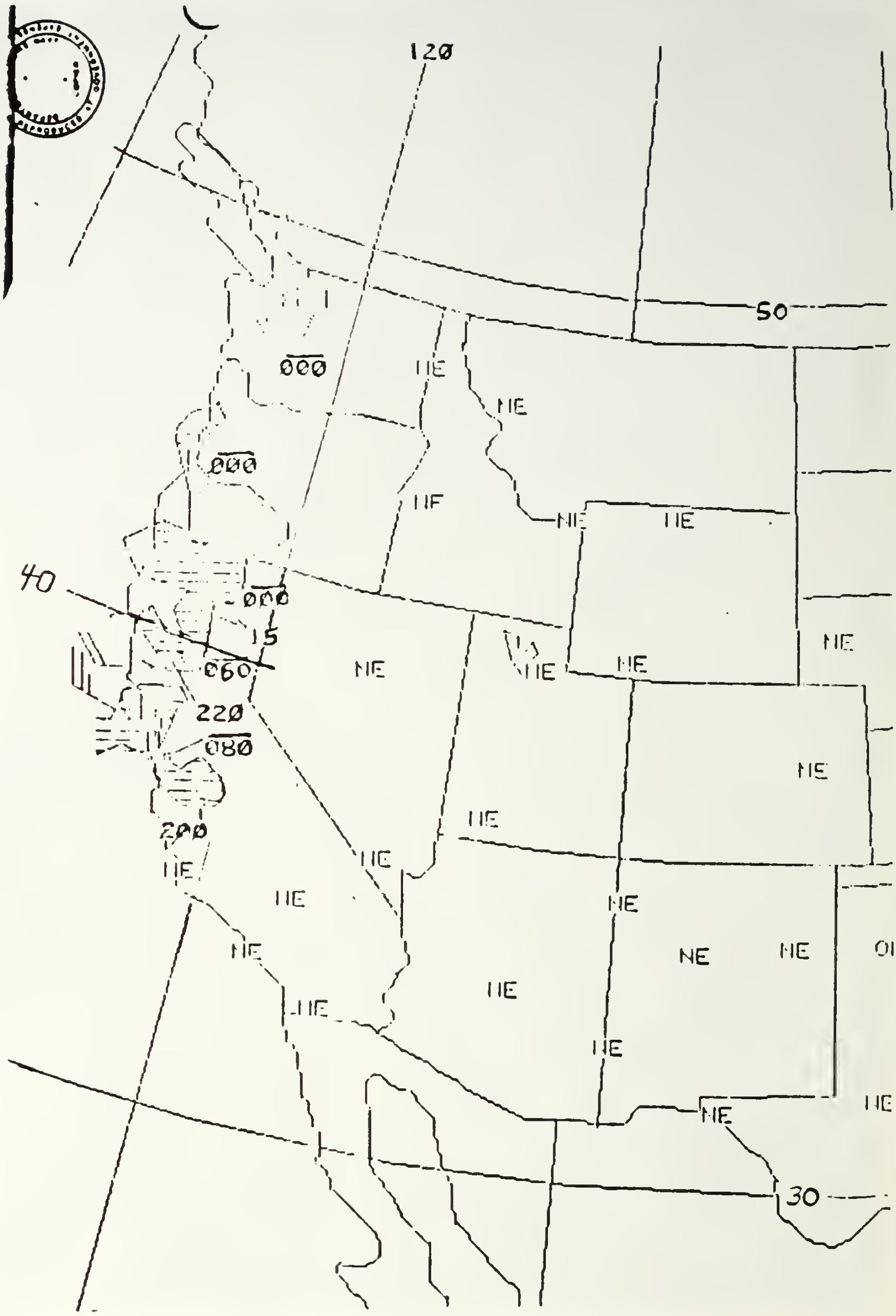

Figure 12. NMC Radar Summary Chart for 1830Z
on 4 December 1986

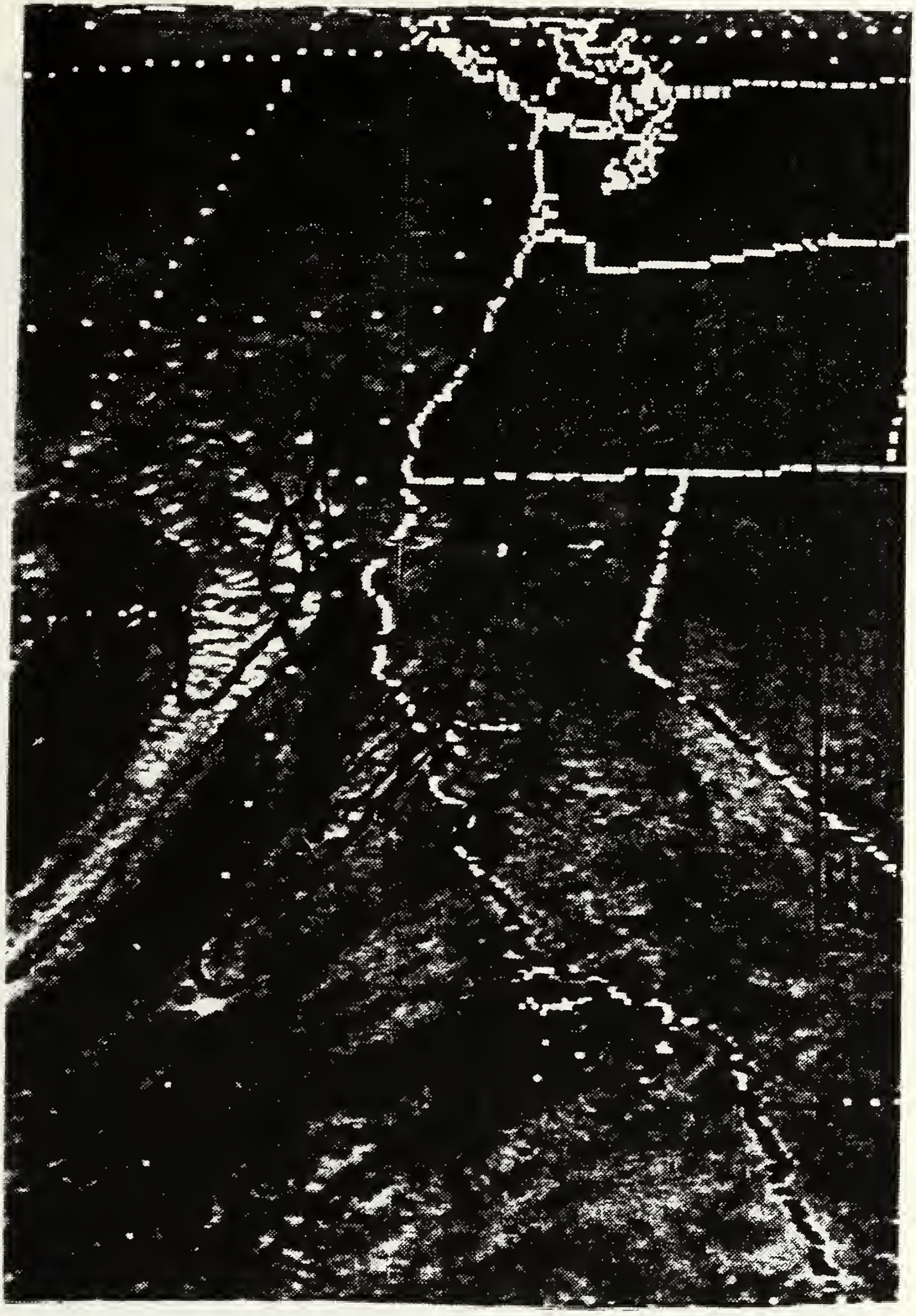

Figure 13. NESDIS Technique overlayed on High Resolution GOES-6 Visible Image for 1901Z on 4 December 1986

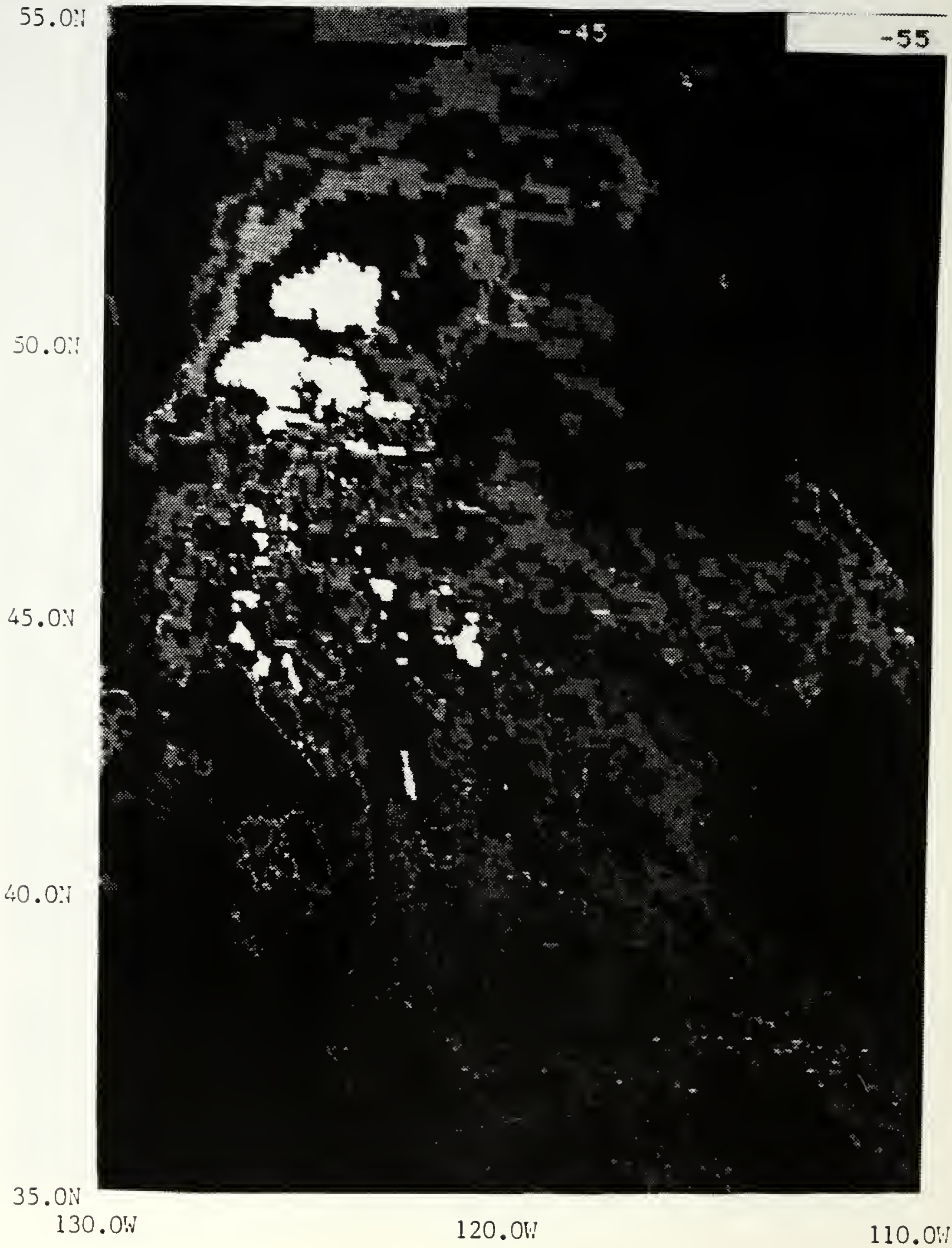

Figure 14. Infrared Technique (-25° C to -55° C)
Image for 1830Z on 4 December 1986

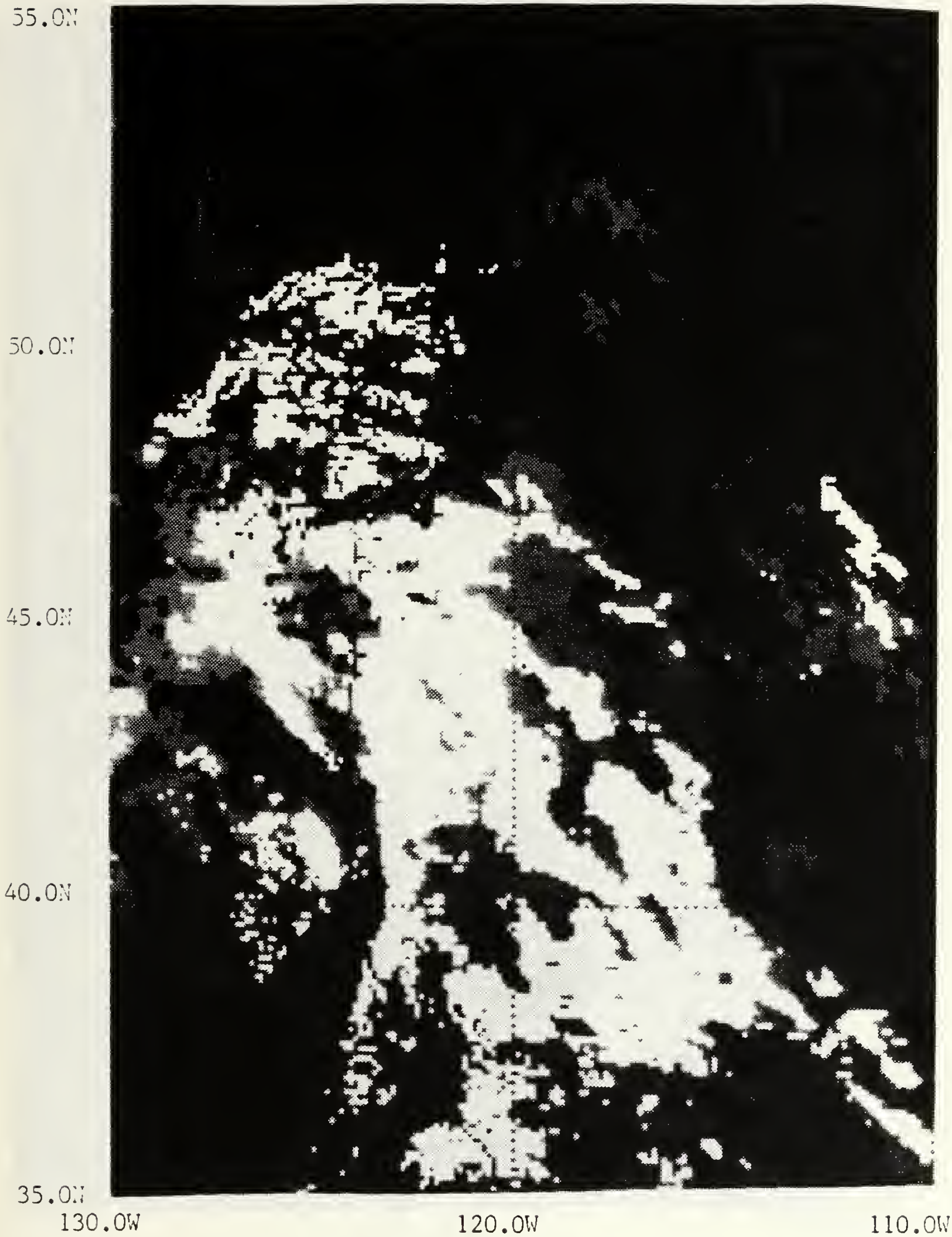

Figure 15. NPS Model Results for 1830Z
on 4 December 1987

Figure 16. Bispectral Image for 1830Z
on 4 December 1986

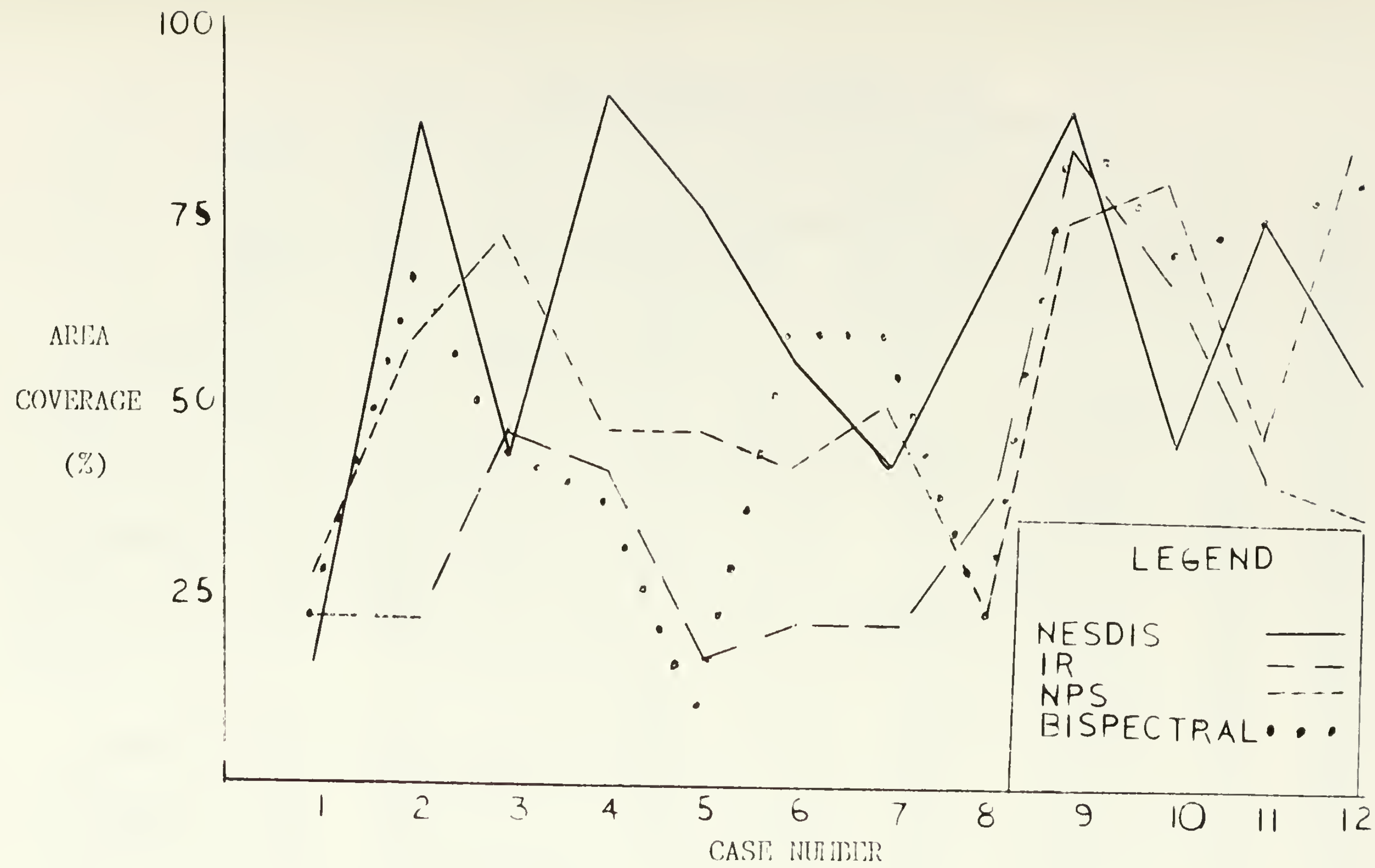

Figure 17. Comparison of Area Coverage by Technique

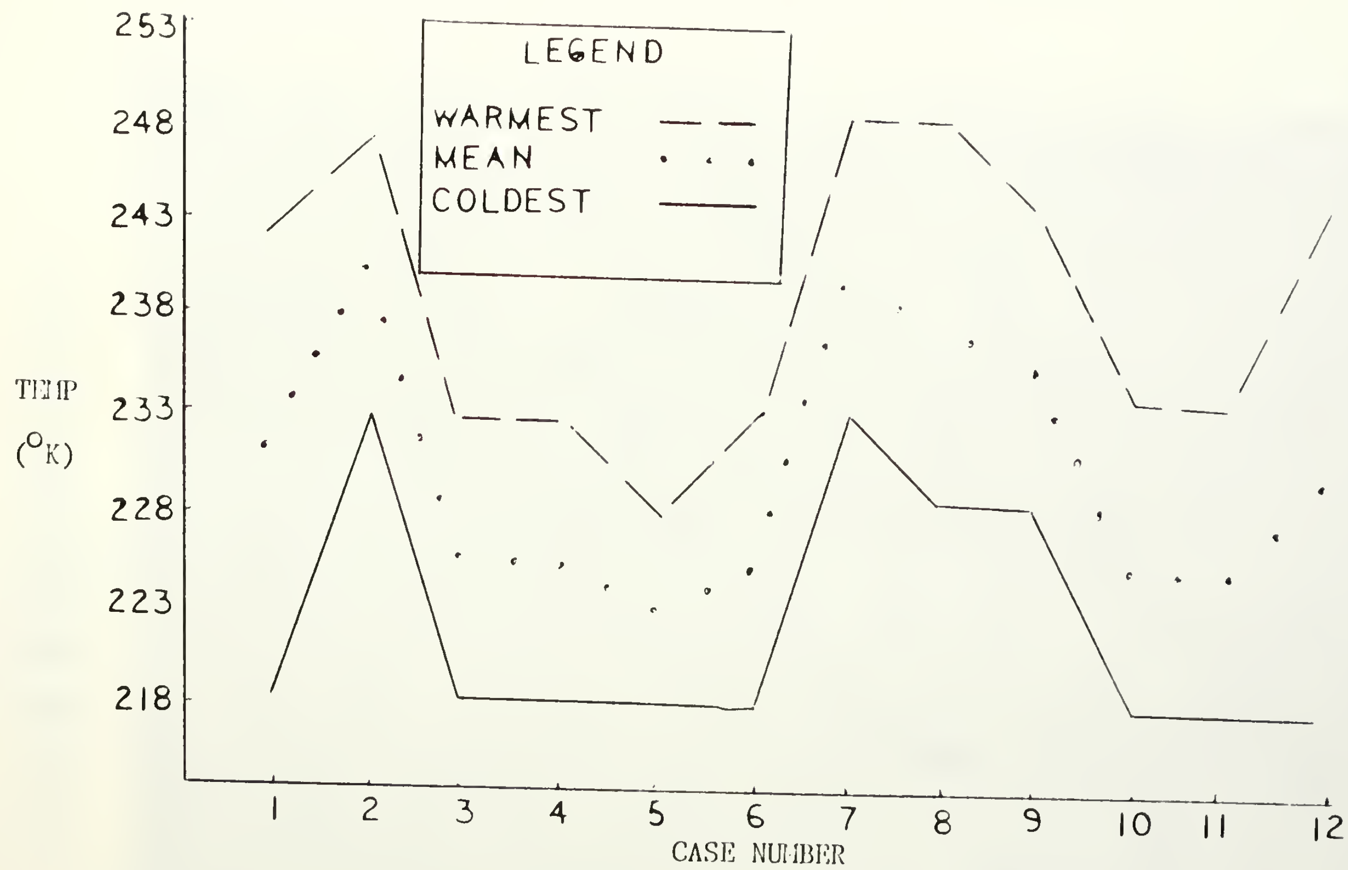

Figure 18. Cloud-Top Temperatures Correlating with Observed Precipitation

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